Phase modulation with polymer-dispersed liquid crystals

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ABSTRACT

We report on work on producing phase-only polymer-dispersed liquid crystals for use in spatial light modulators for adaptive optics. The aim is to assess the magnitude of the achievable phase shifts and the associated slew rate. We describe our methodology of producing devices and present our initial results.

Keywords: Polymer-dispersed liquid crystals (PDLCs), liquid crystals, phase modulation, adaptive optics

1. INTRODUCTION

There have been a large number of papers written on the use of liquid crystal (LC) devices as wavefront correctors for adaptive optics, many of which have been published in this SPIE series of conferences [1]. They have many attractive features associated with their non-mechanical operation and the fact that they can be scaled to have many pixels. However, their largest problem is their slew rate, which is generally too slow for the correction of atmospheric turbulence. This problem is discussed in depth in reference [2]. Dual frequency LCs have provided a partial solution, and results of high speed wavefront control and correction have been published by ourselves and others [3-6]. Despite these results, the control of dual frequency LCs is not simple, and therefore we have also been investigating other technological solutions to the problem of high speed – high stroke phase modulation.

Improvements in LC switching speeds can be made by introducing a small amount (typically 1-10% by weight) of an optically transparent polymer (whose refractive index matches that of one of the LC's indices) to the liquid crystal. The result is a polymer network liquid crystal (PNLC), also known as a polymer-stabilised liquid crystal. A loose network of polymer chains permeate the liquid crystal, increasing the restoring force that the LC molecules experience when applied voltages are removed, and also marginally increasing the required switching field. An infra-red light modulator made using this idea displays phase shifts of one full wave within 2ms, requiring just over 7V/μm to drive the device [7]. The polarisation dependency of such devices means that multiple devices (with orthogonal alignment) need to be employed if unpolarised light is to be used. Alternatively, the device could operate in reflection mode in conjunction with a quarter-wave plate [8], however both these solutions add greater complexity to the device and increase losses caused by scattering and reflection.. PNLCs remain a subject of continued research, and an increasing number of publications describe applications of PNLCs for other switchable optical devices such as lenses [9], microlenses [10, 11] and prism gratings [12-14].

If one increases the amount of polymer within the mixture to approximately 30-50% by weight, a polymer-dispersed liquid crystal (PDLC) is formed, and switching speeds can usually be further improved. In a PDLC small droplets (typically 5-30μm in size [15]) of nematic LC material are distributed in a polymer network. PDLCs have traditionally been applied to display applications, as they switch between scattering (opaque) and transparent modes. In the off-state, the optical axes of the individual LC droplets are randomly oriented and the bulk material therefore scatters light. When an electric field is applied (typically 2 to 10V/μm [15]), all the optical axes align and match that of the polymer, and the bulk material switches to being transparent in around 1-40ms [16]. This scattering mode of operation of PDLCs is clearly not suitable for adaptive optics. However, if the droplet sizes of nematic LC can be made to be smaller than the wavelength of light, then scattering is minimized and the bulk material displays an effective average refractive index which can be controlled by the application of an electric field. It is therefore possible to construct a phase-only modulator.

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There are a number of potential advantages of using phase-only PDLCs (or nano-PDLCs). The first is that the response time of the cell should be greatly improved, because the relaxation time scales quadratically with droplet size [17]. The distance between the LC material and the polymer network (which provides a restoring force when the electric field is removed) is tiny compared to the relative large cell thickness of a conventional nematic LC cell, and therefore the turn-off time is greatly enhanced. The second advantage is that the phase shift should be polarization insensitive, due to the random alignment of PDLC droplets in the off state. Furthermore, in a conventional cell, as the thickness is increased to increase the total available stroke, then the LC molecules in the centre of the cell interact more weakly with the boundary alignment layer and relaxation times become slower. In theory, in a PDLC the response time should be approximately independent of the cell thickness, because the polymer network is distributed throughout the full cell thickness, enabling simultaneously a large stroke and rapid response. The disadvantage is that these increased alignment forces mean that higher voltages are required to achieve a given phase shift.

There are an increasing number of papers published in the field of nano-PDLCs. Holographic PDLCs (H-PDLCs) are an especially active area of research [17-19], where a rapidly switchable diffraction grating pattern is desirable. Other switchable applications include lenses [20], microlens arrays [21] and prisms [22]. However, their application to wavefront correction and adaptive optics has not yet been fully investigated. It is therefore the aim of this work to assess the utility of nano-PDLCs in adaptive optics, by assessing the achievable stroke (and corresponding required driving field), response times and slew rates. This paper represents the results to that investigation so far.

2. EXPERIMENTAL

2.1 Construction of phase only PDLC cells

PDLCs are made by mixing nematic liquid crystal with an optically transparent, UV-curable monomer. This mixture is then introduced to the cell cavity before being illuminated with UV light. As polymerization occurs, phase separation of the liquid crystal and the polymer takes place. Liquid crystal droplets become encapsulated within the polymer matrix. It is the rate of this phase separation, and also the initial concentration of LC and monomer that controls the PDLC droplet size. For phase modulation, one requires droplets of sub-wavelength dimensions to avoid light scattering in the off-state. Therefore, to achieve such nano-sized droplets, one must use a low concentration of LC (large monomer concentration). One must also polymerise the monomer at a very rapid rate, to avoid droplet aggregation. However, it is possible that droplets can be formed that are smaller than is necessary to avoid scattering, resulting in PDLC cells with low available stroke and very high operating voltages. An optimum concentration and curing speed is therefore reached, which creates droplets that are only just small enough to reduce scattering to an acceptable degree.

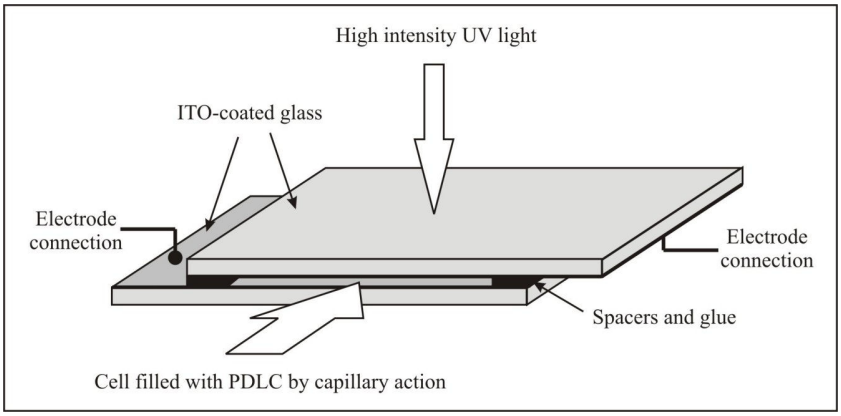


Fig 1. Construction of a PDLC cell.

The nematic liquid crystal E7 (also known as BL001) (Merck) was mixed with the UV-curable monomer, Norland Optical Adhesive 81 (NOA81). A variety of concentrations were tested, ranging from 25% E7, 75% NOA81 up to 35% E7, 65% NOA81. Care is taken to avoid any UV exposure whilst mixing is taking place. Dust and other airborne contaminants were also minimized by carrying out construction within a laminar flow cabinet of class 100 standard.

Cells were made by first preparing two thoroughly cleaned 20mm x 15mm glass slides, coated with electrically conductive but transparent indium-tin oxide (ITO) (Merck). Non-conductive spacer beads (Merck) of 10 and 20μm were then mixed into a UV-curable adhesive (Loctite Glass Bond). This was then used to glue together the two glass slides (ITO facing inwards), as detailed in figure 1. Thicker cells were also made by using strips of acetate film of 50μm thickness as spacers. Additionally, for comparison purposes, some 10μm spaced pre-fabricated empty cells were purchased from EHC Co. Ltd., which also comprised of glass substrates with ITO electrodes (no polyimide alignment layer).

After the glue had been cured under UV light, the empty cell was ready to be filled. This was done by capillary action, introducing the mixture of LC and monomer dropwise to the edge of the cell. Due to the high viscosity of the mixture, filling may take several minutes, or up to an hour. Once filled, the cell was exposed to high intensity UV light ($150mW/cm^2$, 365nm) (Dymax 2000 flood lamp). Under these conditions, a 1 minute exposure was found to be sufficient for polymerisation within the cell to occur to completion. In theory, a longer exposure would not be problematic. However, the curing process is also temperature sensitive, so to minimise excessive heat build-up in the cell the UV exposure time is minimised.

2.2 Testing of PDLC phase-voltage relation and of switching speed

Phase-voltage characteristics for the PDLC cells were determined through the use of a Zygo interferometer, operating at 633nm, whilst simultaneously applying an AC driving field to the cell's electrodes. The high voltages required were generated through the use of a resonant system of amplification. This meant that the frequency of the applied field was kept constant for each cell thickness, and ranged between 655Hz and 925Hz., depending upon the thickness (and therefore the capacitance) of the cell.

Switching speeds were also determined through interferometry (figure 2). A helium-neon laser (633nm) illuminated the PDLC cell, whilst a photodiode and digital storage oscilloscope analysed the reflected light intensity fringes (produced by front and back reflections from the cell). When the driving field was applied and then removed, the resulting phase change caused movement of the fringes, which could be detected as a change in light intensity. Voltages were selected that generated an overall phase shift (double-pass) of half a wave (from a dark fringe to a bright fringe, or vice-versa). The time taken for the light intensity to fall (or rise) to 90% of its final value was recorded as the response time of the PDLC cell.

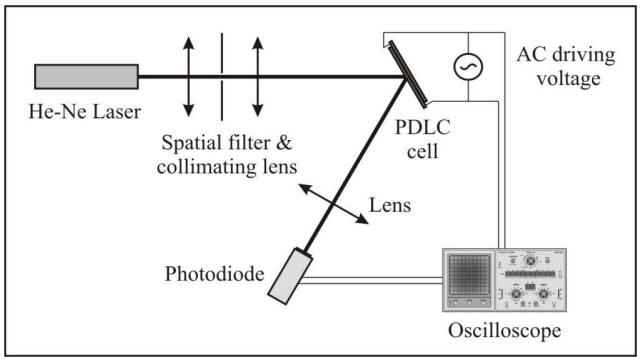
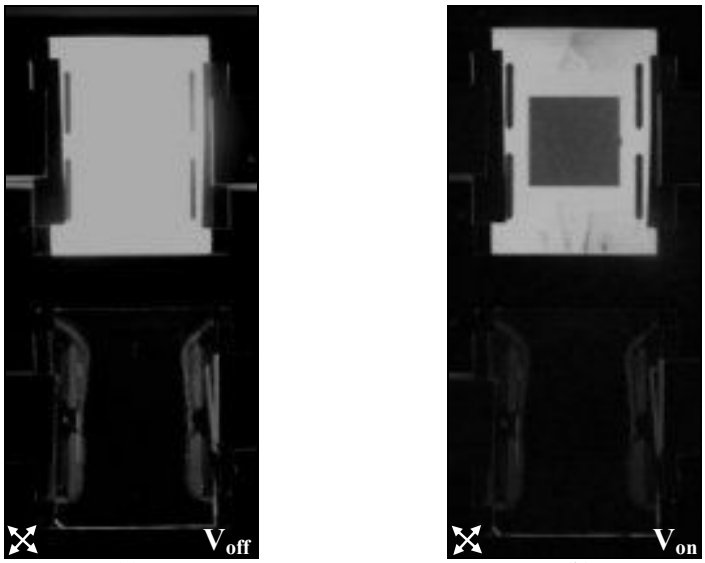


Fig 2. Experimental arrangement for measuring PDLC response times.

3. INITIAL RESULTS

The initial goal was to successfully create a phase-only PDLC (nano-PDLC). After testing a variety of PDLC concentrations the optimum was found to lie at a ratio of 28% LC, 72% NOA81 by weight. At this ratio, cells appeared transparent and displayed a low amount of scattering (although some small degree of scattering was apparent in the thickest cells). Higher LC concentrations resulted in PDLC cells of a milky appearance caused by light scattering from large droplets. Concentrations of LC less than 30% also made scattering-free cells. However, with less LC within them, these cells would require extremely large voltages in order to generate the same field. 28% LC cells were

therefore chosen for all subsequent analysis of the performance of our phase-only PDLCs. No significant differences were noted between the filled EHC 10μm pre-fabricated cell and our home-made 10μm cell. The home-made cell shows slightly more scattering than the pre-fabricated cell, probably due to inferior glass quality and cleaning techniques.



(a) (b)

Fig 3. A conventional LC cell with homogeneous alignment (top) compared with a nano-PDLC cell (bottom), between crossed polarisers (at 45° to rubbing direction of LC cell), with (a) no applied field and (b) with an applied field.

Figure 3 shows images of our 10μm thick nano-PDLC cell and also of a conventional LC (E7) cell with homogeneous (rubbed) alignment. In comparison to the conventional LC cells, when our PDLC cells are rotated with respect to the polarisers, no change is observed, indicating polarisation independency. This means that LC alignment is random from one droplet to another. Between crossed polarisers, our PDLCs also show no discernable difference when a voltage is applied (as would be expected for a phase-only modulator). Cells are also of good optical quality with little observable scattering at optical wavelengths. This implies that PDLC droplets within the cell are of nano-scale dimensions as desired. Rigorous determination of the exact size of PDLC droplets was not carried out in this initial investigation. However, future work may involve the use of electron microscopy to help determine droplet size and morphology, both of which are of concern when attempting to optimise switching speeds and voltages.

Figure 4(a) shows the voltage-phase relation for a 10μm thick nano-PDLC cell, showing the familiar sigmoidal pattern associated with liquid crystals. Half a wave of phase shift has been generated by applying a field of 100V/μm (1kV with a 10μm cell). At this field strength and above, LC directors are fully rotated to align with the field, and no further phase shift can be achieved. In order to obtain a larger stroke, one must construct a cell of greater thickness.

Figure 4(b) shows the voltage-phase relation for a 50μm thick nano-PDLC cell. At 1.5kV, the limit of our equipment was reached, and thus the full range of the cell's available stroke is not known. However, it is clear that the thicker 50μm cell displays a much larger phase range than the 10μm cell. It is also apparent that the available phase shift at a given field strength is larger for the thicker cell than it is for the thinner cell. This is likely to be caused by the fact that the molecular rotation angle in a PDLC is a function of field strength (unlike a conventional LC when it is, to first order, a function of voltage), and so the rotation angle will be the same in both cells, but the thicker cell simply has more path length. The disadvantage of the thicker cell however, is the requirement of larger voltages to generate the same field strength.

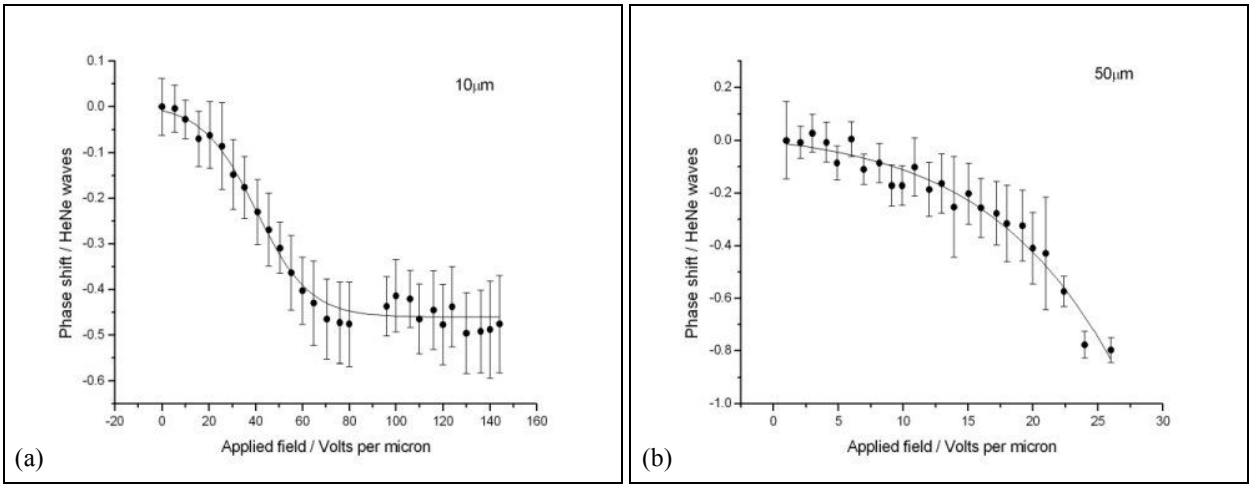


Fig 4. Voltage-phase relations for nano-PDLC cells of (a) 10μm and (b) 50μm.

The high voltage requirement of nano-PDLCs is a consequence of having very small PDLC droplets. Smaller droplets mean a larger surface area of polymer/liquid crystal interface, which in turn results in stronger anchoring of the liquid crystal to the polymer and to its intrinsic alignment orientation. Much larger voltages are therefore required to overcome this anchoring. Whilst such high voltages might be considered unsuitable for some applications, it is anticipated that they should pose no real problem in adaptive optics and atmospheric turbulence correction, where high voltage equipment often already exists for driving piezoelectric actuators in segmented mirrors and other similar devices. It is also hoped that any inconvenience of these larger voltages is compensated by their rapid switching speeds.

Nano-PDLCs are expected to display rapid switching speeds compared to conventional LCs and PDLCs. As with all liquid crystal devices, switch on times are faster than switch off times. This is due to the fact that during switch-off, there is no electric driving field to help LC directors to rotate to their original alignment, and instead, they rely upon the restoring force of the anchored LC molecules at the polymer interface. In our experiments however, switch-on and switch-off times are fairly similar. The 10μm cell shows switch-on speeds of less than 2ms, and switch-off speeds of about 2ms (figure 5). (A 10Ω resistor was used to short the terminals of the cell when measuring switch-off times, to assist in rapid dissipation of the electric field. The upper trace, displaying the unamplified driving field, therefore does not flat-line at the point of discharge). The 20μm cell also switches on in just under 2ms, and off in approximately 2ms (figure 6). These times are very approximate and represent maximum possible values, because our system of voltage driving is not capable of instantaneous voltage changes and has a rise and fall time that is comparable to the response time of our PDLCs. Evidence that our cells are capable of switching faster than these quoted values is also apparent when one considers the frequencies of our driving voltages. Measurements were taken at resonant frequencies of 925Hz (10μm cell) and 655Hz (20μm cell). At these frequencies, the PDLC is capable of switching at speeds comparable to the oscillation of the AC field. Oscillations of the photodiode output (synchronised with the driving field) can often be seen whilst the PDLC cell is switched on. Ideally, one requires a system capable of driving similar voltages at higher frequencies, which oscillate faster than the PDLC is capable of responding.

Theory suggests that the two different thickness cells should switch off at about the same speed as each other. This is due to switch-off times being largely dependent upon droplet size (and not the distance of the droplet from any cell boundary or alignment layer, as is the case for conventional LC cells). Our results initially indicate that this is indeed the case. This means that thicker cells with larger available stroke could potentially be made with hopefully negligible effect on switching speed. The only concern is if sufficient a voltage can be supplied to the cell to utilise the full stroke of the device.

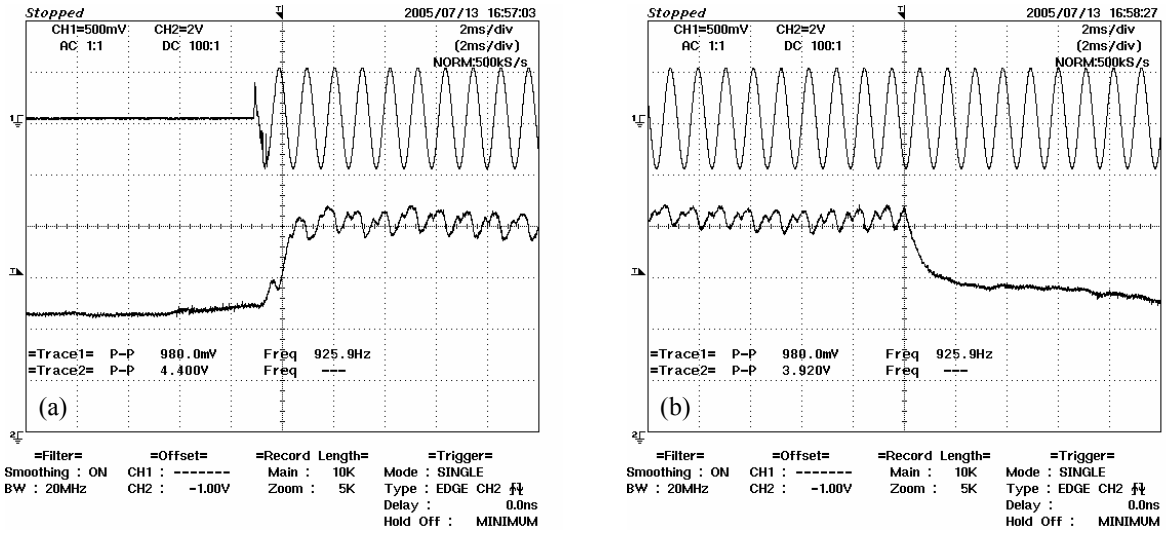


Fig 5. Response times for 10μm thick nano-PDLCs during (a) switch-on and (b) switch off. The upper trace represents the driving field (before amplification), whilst the lower trace represents the photodiode output.

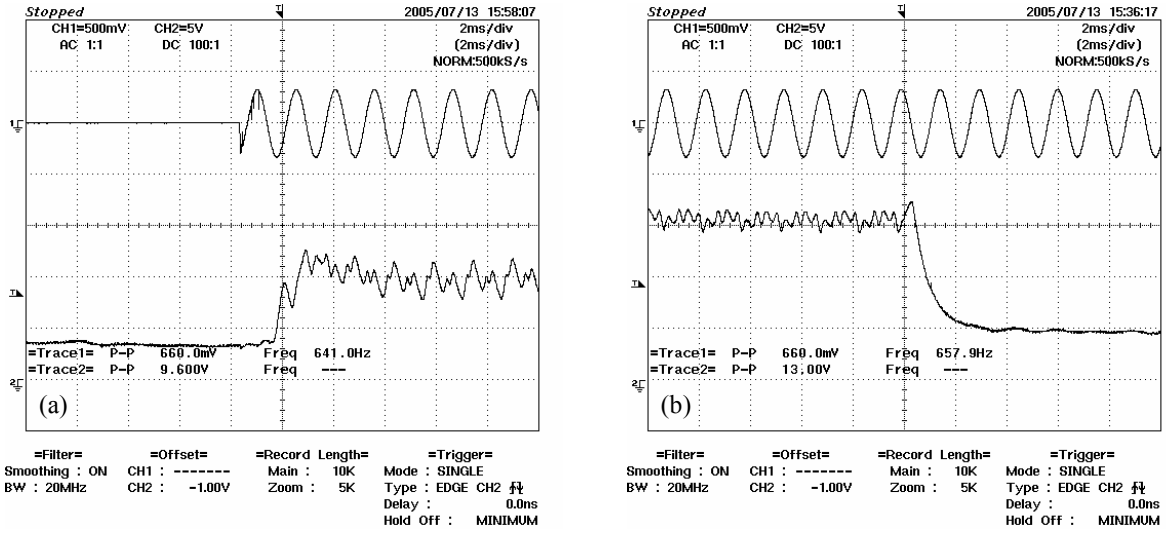


Fig 6. Response times for 20μm thick nano-PDLCs during (a) switch-on and (b) switch off. The upper trace represents the driving field (before amplification), whilst the lower trace represents the photodiode output.

Continuing on from this work will be a more rigorous investigation of the total available stroke of thick (approximately 100μm) nano-PDLC cells using larger voltages and frequencies than are currently available to us. Performance might also be improved by increasing the concentration of LC whilst retaining nano-sized droplets. This would require faster curing at even higher UV intensities (perhaps with a UV laser), but could increase the stroke of our devices without sacrifice to switching speed or driving voltage. It would also be useful to investigate the claims of other publications in the field of nano-PDLCs, which suggest that a surfactant could be added to the PDLC mixture to help reduce the switching voltages required (and maybe also to help improve switching times) [17, 18]. Results to this work have shown that it may be possible to achieve response times of approximately 50-200μs, using fields of around 5-15V/μm.

4. CONCLUSIONS

We have reported our progress in assessing the suitability of PDLCs as wavefront correction devices. Our initial results show that PDLCs with nano-scale droplets can be successfully made, which have low scattering at optical wavelengths and are capable of phase modulation. In comparison to conventional LCs, these devices are polarisation insensitive and have faster switching speeds (approximately 2ms for a quarter wave of phase shift), comparing favourably with the requirements of adaptive optics.

Increasing the thickness of a PDLC cell (in an attempt to increase the total available stroke) has a minimal effect upon the switch-off response time when compared to conventional LCs. This means that phase correction over multiple waves should be possible. The potential disadvantage of our nano-PDLCs is the large switching voltages required to operate them (typically 100V/μm for full stroke). However, with continued work, it is anticipated that the required fields can be reduced, and switching times can be further improved.

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